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Initial Development of Improved Aircraft Cargo Compartment Fire Detection Certification Criteria.

Abstract

Most of the cargo compartments on passenger carrying aircraft are required to have fire detection systems that provide a visible indication to the flight crew within one minute from the start of a fire. Flight tests are required to demonstrate compliance with these regulations. The fire detectors in use today are either photoelectric or ionization smoke detectors. While these detectors are effective at detecting actual fires they are also prone to alarm from airborne particles not associated with fires. The use of multiple sensors and appropriate alarm algorithms have the potential to better discriminate between actual fires and nuisance alarm sources. Certification guidelines for using these types of fire detectors on aircraft do not currently exist.

Testing is being conducted to define the types of fires that should be detected and the production of smoke, heat and gases from these fires. The tests will be conducted in various sized cargo compartments to determine if the threshold fire size for detection should vary with compartment size and shape or if the fire size should remain constant and the time to detection should be varied.

Concurrent with the initial fire testing, a transient computational fluid dynamics simulation tool for the prediction of smoke transport in cargo compartments is being developed. This simulation tool will couple heat, mass, and momentum transfer in a body fitted coordinate system in order to handle a variety of cargo bay shapes and sizes. Comparing the predicted results with the results obtained from the full-scale fire tests will validate the CFD model. Ideally, such a physics based CFD simulation tool can be used during the certification process to identify worst case locations for fires, optimum

placement of detector sensors within the cargo compartment and sensor alarm levels needed to achieve detection within the required time.

Testing is being conducted at the FAA Technical Center. The code is being developed by Sandia National Laboratories. Additional partners in the project include the National Institute of Standards and Technology (NIST) and the National Aeronautics and Space Administration (NASA) Glenn Research Center.

1. Introduction

Incidents of aircraft cargo compartment inflight fires are very rare events but as with all fires the consequences can be severe. Reliable detection and effective suppression or fire containment within the cargo compartment is perhaps more critical than in other occupied areas due to the inability to quickly land the aircraft and perform a rapid evacuation. Aircraft operate on some routes that could be in excess of three hours flight time from a suitable airport. Even on domestic flights, 15 to 20 minutes is often needed to descend from cruise altitude and land before an evacuation can be initiated.

The number of incidents of false alarms from aircraft cargo compartment detection system has been steadily increasing as the number of aircraft in the US fleet increases [1]. In addition, the ratio of false alarms to the detection of actual fires in cargo compartments is also increasing. For the period 1995-1999, the ratio was approximately 200:1. Because the majority of cargo compartments on passenger carrying aircraft are inaccessible during flight, the required procedure in the event of a cargo fire alarm is to discharge fire suppression agent if available and divert and land at the nearest suitable airport. Not only are the direct costs of unnecessary diversions due to false alarms significant but they also raise safety concerns. Some of those concerns include passenger and crew injuries in the event of an emergency evacuation and the possible increased risk of an accident due to landing at unfamiliar airports, changes to air traffic patterns, shorter runways, and inferior navigation aids.

2 Certification of Fire Detectors

The FAA, along with other regulatory agencies throughout the world, require that aircraft cargo compartment fire detection systems provide a visible indication to the flight crew within one minute after the start of a fire [2]. A flight test is required to demonstrate compliance with the regulation. The flight test is conducted during the certification process for a new aircraft type or when there has been a significant change in the fire detection system. The fire detectors that have been exclusively used in aircraft cargo compartments have been photoelectric or ionization smoke detectors. They are either spot detectors or in aspirated systems. A wide variety of smoke sources have been used during the required flight tests to demonstrate the functioning of the detection system. Some examples include burning tobacco, rope and chemicals and a variety of theatrical smoke generators. The methods for generating smoke and the quantities permitted in different size cargo compartments have evolved within the different certification offices over the years based on individual preferences. The FAA has issued guidance material on smoke sources and a visual representation of the appropriate quantity of smoke. However, the precise quantity of smoke is still subjective and there is currently a lack of standardization regarding exactly what the detection system is supposed to detect within one minute. Multi sensor detectors have not previously been used in aircraft cargo compartments but would seem to have the capability to reduce the current rate of false alarms. However, there are infinite combinations of threshold alarm levels, rate of rise values, and number of sensors that can be used to trigger or suppress an alarm. There is currently very little information available for the FAA to determine what are appropriate alarm levels and algorithms for cargo fires. The environment inside a cargo compartment is subjected to fairly rapid changes in temperature, pressure and humidity as well as exposure to the exhaust from airplane and service vehicle engines.

In addition to the need to better define what should be detected, a parallel effort is underway to develop a transient computational fluid dynamics simulation tool for predicting the transport of smoke, heat and gases within a cargo compartment. Full-scale cargo fire tests will be used to validate the model. Due to the high cost of flight testing, extensive ground tests are typically conducted to define the best location for fire detectors, the worst location for the fire source and the alarm levels necessary to

achieve detection in less than one minute. If enough confidence is developed in the model it could replace much of the current testing.

Research has been conducted by NIST in support of this joint project. The first phase of that effort has been a literature search to attempt to document all of the fire detection technologies that currently exist and assess their suitability for aircraft cargo compartments [3]. In addition, they have conducted testing in a Fire Emulator/Detector Evaluator apparatus to document the response of existing aircraft smoke detectors to three fire sources and three nuisance alarm sources.

NASA Glen Research Center is also contributing to this project through funding for the CFD model development and research into miniature gas sensors that could be used in multi sensor fire detectors.

3. Fire Sources

The FAA Technical Center has undertaken an effort to standardize the fires to be detected and develop data for selecting appropriate alarm levels and algorithms. It is desirable for the standardized fires to be both repeatable and realistic. Anything imaginable can be carried in an aircraft cargo compartment and there is no typical cargo fire. The standardized fires described in EN 54 and UL 217 were initially considered but it was felt that those fires did not produce a realistic enough mix of the kinds of gases that would reasonably be expected from a cargo fire involving typical luggage material. Two new fire sources were developed and have undergone initial testing with promising results. Both fire sources use a mix of six plastic resins in pellet form that are heated and pressed into a 4" by 4" by 3/8" molded resin block. A length of nichrome wire is embedded within the resin block and is used as a heat source. A smoldering fire source can be produced by energizing the nichrome wire alone. The same resin block is used to produce a flaming fire source by pouring 2 ml of heptane onto the resin block and simultaneously igniting the heptane and energizing the nichrome wire. The resins used are: Nylon, Polyethylene, Polyvinyl Chloride, Polystyrene, Polybutylene Terephthalate, and Polyurethane. In the Cone Calorimeter tests, it was shown that the

burning behavior of both fire sources and the production of combustion gases is very repeatable [4].

4. Test Results

The FAA Technical Center has conducted tests in a below floor cargo compartment of a Boeing 707 test article. The compartment is instrumented with smoke meters, thermocouples and gas analyzers. It also simulates typical ventilation flow in the form of leakage around the perimeter of the cargo door. Figure 1 shows the 707 test article.

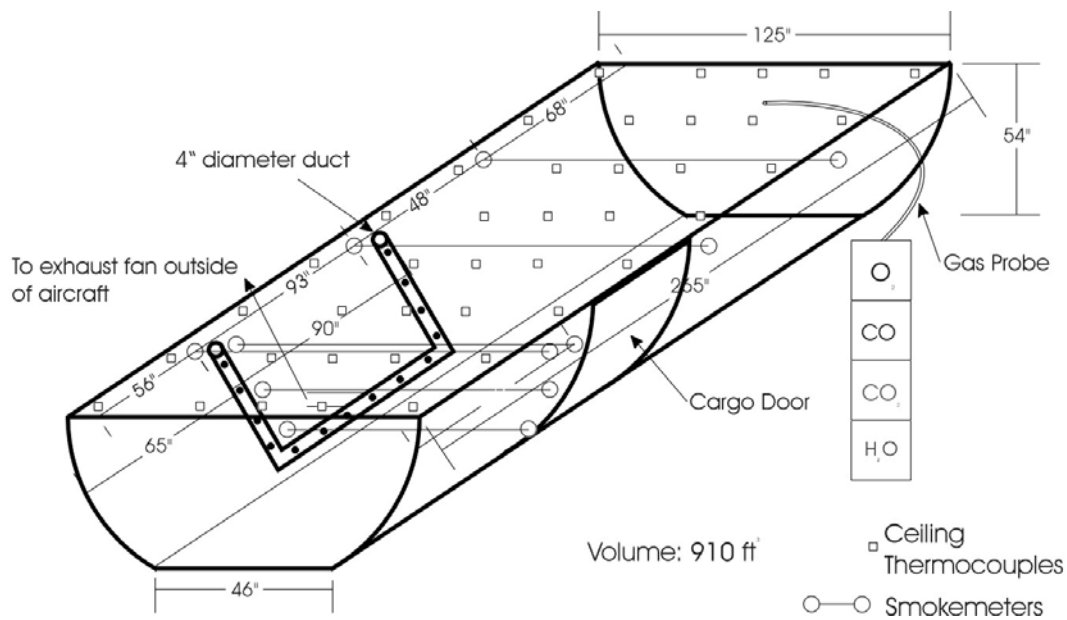


Figure 1. 707 Forward Cargo Compartment

The initial testing attempted to quantify the smoke output from a smoldering suitcase. Identical suitcases were purchased and filled with a mix of cotton and synthetic rags. A coil of nichrome wire, wrapped around several paper towels and connected to a 110 VAC supply was used as the ignition source. Figure 2 shows the smoke levels measured by the mid ceiling smoke meter during six smoldering suitcase tests. As expected, there was considerable variation in the quantity of smoke produced despite a relatively uniform fire load. Time zero on the chart is the time when smoke was first observed. That time was fairly subjective because of the different behavior from tests to test. An easily discernible smoke plume would start for some tests while for others very light

wisps of smoke could be seen intermittently before a steady plume was observed. The rectangular outline on the graph shows the desired target for the quantity of smoke produced. The width of the box is the 60 second window in which detection is currently required. The height of the box represents the range of alarm levels required by Technical Standard Order (TSO) C1C which applies to aircraft cargo compartment fire detectors. It would obviously not be practical to expect a detector to alarm in the required time and at the required alarm level if the quantity of smoke it was exposed to did not fall within that range. The smoldering suitcase did not consistently produce the desired smoke quantity.

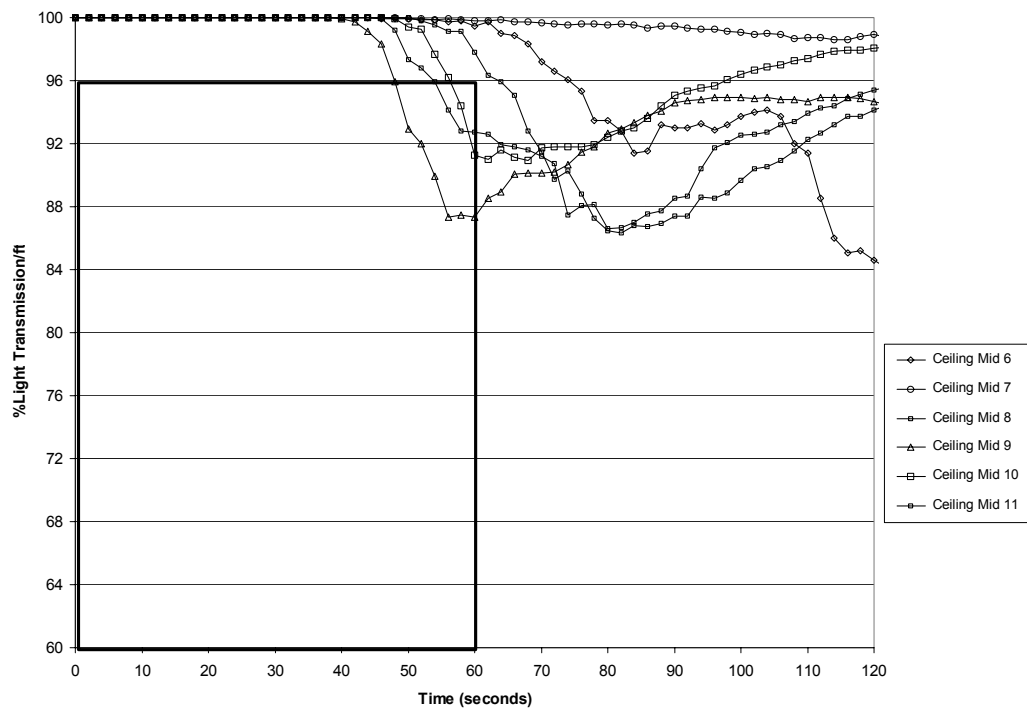


Figure 2. Smoke levels from a smoldering suitcase.

The results of initial testing using the molded resin block in a smoldering state is shown in Figure 3. The results show better repeatability and the smoke that is produced falls within the desired quantity and allotted time for this particular volume cargo compartment. The flaming fire scenario also produces the desired smoke quantity.

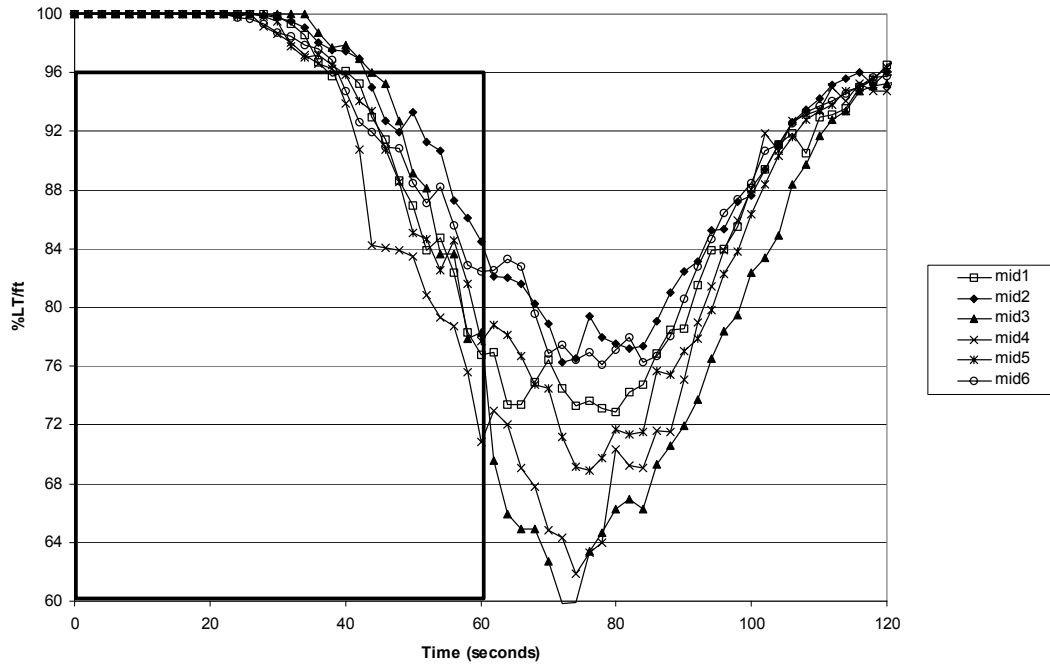


Figure 3. Smoke levels from smoldering resin block

The testing of both the smoldering and flaming resin blocks in the Cone Calorimeter employed a FTIR mass spectrometer for gas analysis. The data from those tests will be used to provide the source terms for heat release rates and smoke and gas production in the CFD model. Additional testing is also planned in the 707 cargo compartment as well as larger cargo compartments to measure the concentrations of various gases. The sample probes and the smoldering and flaming fire sources will be placed in various locations. The data will be used to validate the CFD model and to provide some guidelines for selecting appropriate alarm algorithms for multi sensor fire detectors.

5. Computational Fluid Dynamics Model

A computational fluid dynamics simulator is currently being developed at Sandia National Laboratories to predict the transport of smoke in cargo compartment fires. The targeted platform is a midline personal computer, i.e., 128 MEG of memory with a 750 MHz Intel® Pentium® III processor. The simulation tool is to run quickly and efficiently at modest computational grid sizes (10-30K) in an effort to provide a convenient platform on which to identify worst case fire location scenarios for use during the certification

process. It is anticipated that the total “time to detection” simulation will be on the order of one minute, whereas the total computational run time will be on the order of hours.

5.1 Turbulent Flow Simulation Background

Accurately modeling the complex physical phenomena associated with heterogeneous combustion often requires physical models that couple turbulent fluid flow, heat and mass transfer, radiant energy transfer, and chemical reaction. The appropriate physical governing transport equations are discretized and solved on a computational mesh. Unfortunately, the computational expense of solving the turbulent reacting system directly for all appropriate time and length scales frequently exceeds both the computational resources of the user and the desired cost-to-accuracy ratio. Therefore, models that are largely guided by reasonable engineering assumptions have been developed to decrease the associated computational expense in solving these types of problems while attempting to preserve all controlling physical phenomena.

The description of the conservation of mass and momentum for a continuum fluid are described by the Navier-Stokes Equations [5]. These equations are equally valid for turbulent flows since the molecular mean free path is much smaller than the length scale associated with a typical eddy. Therefore, solving the instantaneous Navier-Stokes equations in a turbulent system would yield an instantaneous velocity field that, over time, would fluctuate about some mean value. In most engineering numerical implementations of turbulent flows, however, the instantaneous equations of motions are not solved due to the excessive computer memory requirements associated with resolving the small length and time scales. Rather, the time-averaged equations are solved. This time-smoothing procedure is accomplished by separation of each independent variable into a time-mean and fluctuating part within the equations of motion and time averaging the result.

The technique of Reynolds averaging the equations of motion leads to cross terms known as Reynolds stresses [5]. These newly created cross fluctuation terms are an artifact of the Reynolds averaging procedure and must be adequately modeled. The proper modeling of these terms represents the classic closure problem of turbulent fluid mechanics.

In variable density flows, the density must also be decomposed and its inclusion within the time-smoothing technique augments the total number of Reynolds stress terms by introducing cross terms involving a fluctuating density component. In such variable density cases, it is convenient to utilize the technique of Favre-averaging [6], which eliminates this complication, by weighting the fluctuating quantities by the instantaneous density before the time averaging step. Upon Favre averaging the variable density equations of motion, triple correlation terms involving variable density terms are, therefore, eliminated. Therefore, the Favre-averaged equations appear to be exactly of the same form as the Reynolds averaged Navier-Stokes (RANS) equations when density fluctuations are neglected.

Most engineering turbulence closure CFD codes employ a form of the Boussinesq [5] hypothesis to model the Reynolds stresses that arise during the time-smoothing procedure. In this formulation, the Reynolds stresses are assumed to act analogously to molecular viscous stresses, i.e., in a gradient-type diffusion relationship. Therefore, the Reynolds stress terms are assumed to be proportional to the mean velocity gradient multiplied by a proportionality constant known as the turbulent eddy viscosity [7]. The closure problem reduces to calculating an appropriate turbulent eddy viscosity by the utilization of models such as the two-equation k - ϵ model [7] that relates the turbulent energy production and dissipation to the turbulent eddy viscosity via the Prandtl-Kolmogorov relationship [7].

5.2 Current CFD formulation

The unsteady, Favre-averaged, three-dimensional incompressible Navier-Stokes equations are solved using a finite-volume method whereby the body-fitted partial differential equations are discretized. The use of a structured body-fitted coordinate system within the CFD simulator is desired in order to adequately represent the curvature of the cargo compartment walls while maintaining a low amount of total required mesh points.

In addition to the time-mean equations describing the transport of momentum, equations describing the turbulent time-mean transport of germane species, e.g., CO, CO₂, soot, etc. can be computed and used for the calculation of point wise mixture properties such as molecular weight and heat capacity. A sensible enthalpy transport equation, including convection heat loss to the cargo walls, is solved to determine the temperature field using the mixture average heat capacity. Radiation effects within the code are currently neglected.

The transient partial differential equation set, in strongly conserved form, is solved for the primitive variables on a collocated grid. A fully implicit scheme, which is first order in time, is used to solve the transient equation set. Face values for the convective terms are determined by the hybrid scheme [8] that results in second order spatial accuracy for Peclet numbers less than 2.0¹ and first order upwind differencing for Peclet numbers greater than 2.0. To overcome the well-known pressure-velocity decoupling that can occur when using a collocated grid, a convective flux interpolation method based on the work of Parameswaran, et al [9] is used. A modified version of the SIMPLE formulation [8] as described within Parameswaran et al. [9] is implemented. In cases where pressurization can occur, the Extended SIMPLE algorithm is used to include low speed compressibility effects [8]. The Boussinesq hypothesis is assumed and the turbulent eddy viscosity is determined by the standard k - ϵ equation [7].

6. Physical fire model formulation

Although it is possible to include physical models that adequately describe the detailed chemical reactions germane to the fire process, such a simulation would likely exceed both the targeted simulation run-time and platform constraints. In fact, detailed multiple step kinetic devolatilization models for the materials common in airplane cargo compartments are not available. Therefore, the CFD simulator will not attempt to model the complex physical process of species devolatilization, chemical dependent heat release, and the chemical reaction interaction between high temperature free radicals. Rather, the CFD simulator utilizes experimentally time-resolved species and heat release data in lieu of simulating the complex physical phenomena associated with physical objects burning.

¹ Second order spatial accuracy is formally true for only purely orthogonal grids.

The CFD simulator, therefore, numerically models the fire by the placement of mass and heat source terms within the right hand side of the appropriate transport equation. The overall volumetric mass source term appears on the right hand side of the following equations: 1) continuity equation, 2) species transport equation (multiplied by the appropriate mass fraction of that particular species), and 3) the momentum equations in the form of a momentum sink. The placement of volumetric heat releases on the computational grid will model the buoyantly induced flow rather than the associated heat release due to both homogeneous and heterogeneous chemical reaction. Although the technique of prescribing source terms is certainly not the preferred method for an entirely predictive CFD code, in this particular application where source terms are available through a detailed time-resolved experiment, it is the preferred method.

7. Mathematical formulation

The partial differential equations describing momentum, species, turbulent energy, turbulent dissipation, and sensible enthalpy transport are linearized and discretized using the finite volume method [8]. The method of finite volume discretization is a conservative approach even at low discretization resolution. The discrete continuity equation, which includes the appropriate discrete volumetric mass source term, is used to form the pressure correction equation [8]. The governing equations are solved iteratively using a segregated approach. Updating the matrix coefficients through each sweep captures the non-linearity inherent to the original PDE equation set. The linear system of equations for the momentum field, species, turbulent dissipation and production, and sensible enthalpy are solved using the strongly implicit method of Stone [10] while the pressure correction equation is solved via a preconditioned conjugate gradient method. A particular time iteration is considered converged when the maximum residual of all individual linear equations is below a user-defined value that corresponds to the desired reduction in the normalized L2 norm.

8. Code Validation and Preliminary Simulation Results

A concerted effort between the FAA and Sandia National Laboratories is underway to validate the CFD model by comparing the simulation results to detailed experiments

that measure species and smoke concentrations at various locations within the cargo compartment. Figure 4 illustrates a preliminary simulated temperature profile ten seconds into a simulation. This initial CFD simulation utilized a heat and mass release rate of 2.25 KJ and 0.05 g/s, respectively. These boundary values correspond to a single instance of time-resolved experimental data for a flaming resin from a FAA cone calorimeter experiment. The total number of grid points represented in this simulation is 10,000.

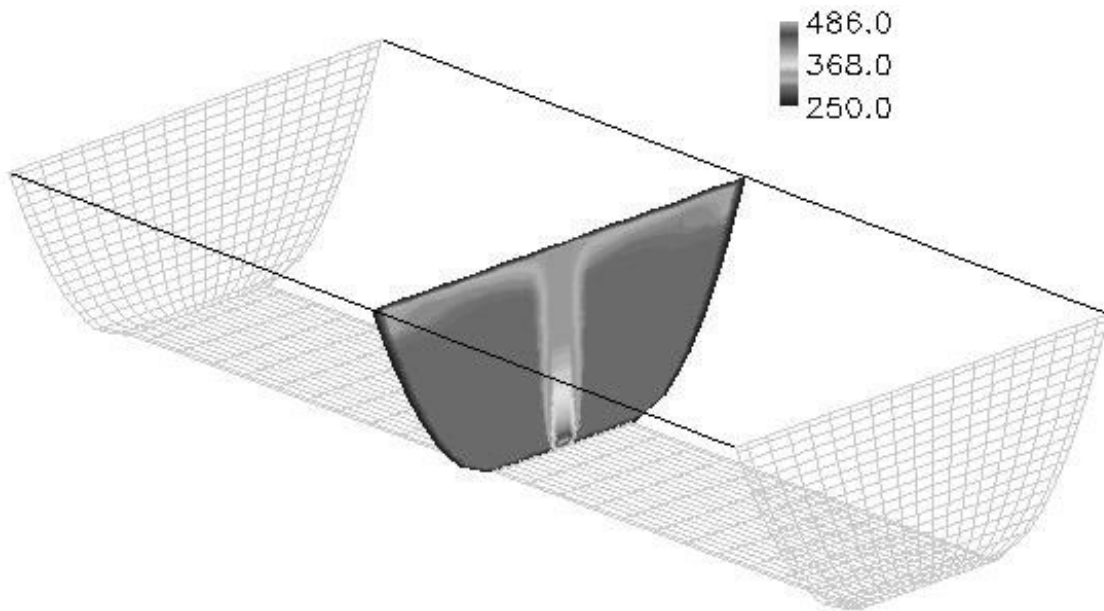


Figure 4. Simulated temperature profile, K, at 10 seconds.

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